Phasing Transformers

E. D. Meyer

1906

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Transformers

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A STUDY

OF

PHASING

TRANSFORMERS

A THESIS

PRESENTED BY

E. D. MEYER

TO THE

PRESIDENT AND FACULTY

OF

ARMOUR INSTITUTE OF TECHNOLOGY

FOR THE DEGREE OF

BACHELOR OF SCIENCE IN ELECTRICAL ENGINEERING

HAVING COMPLETED THE PRESCRIBED COURSE OF STUDY IN

ELECTRICAL ENGINEERING

JUNE, 1906

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JUNE 1906

C. E. Freeman
Par Snow

F. M. Raymond
Dean of Eng. Students

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EVOLUTION OF THE TRANSFORMER.

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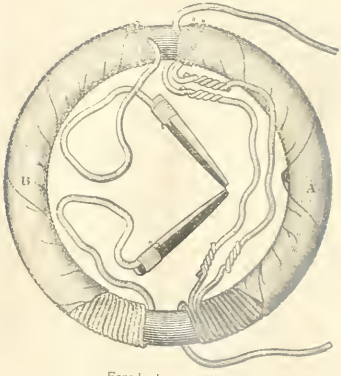
Evolution of the Transformer.

As we wish to write of those discoveries which led up to the invention of the transformer, we must go back to a time, old as compared with the modern development of electrotechnics. For the startingpoint of our observations we shall take Faraday, who, like Newton in mechanics led the way in the domain of electricity, and whose name stands in the most intimate relations with all inventions for the mechanical production of the electric current, and therefore with the later development of electrotechnics.

Faraday, 1831. The most important discovery for which we have to thank Faraday is that of induction. This discovery was made by him in the year 1831 and intimated to the philosophical world in a paper read on the 24th November 1831, appearing in the Transactions of the Philosophical Society in the year 1832.

Faraday's first induction apparatus consisted of two coils of wire, the one being slid over the other. As he was passing the current from a battery through one of these, he made the discovery that each time the circuit of the coil was opened or closed an electromotive force was created in the second coil, which caused a short gush of current or induction current to flow, provided the circuit of this coil was closed, as might be through a galvanometer. The peculiarity of this induced current was that



Faraday's type of transformer.

it only flowed in the second coil during the time the current in the first coil took to reach its normal strength after closing the circuit, or on breaking the circuit during the time the current took to decrease from its normal strength to zero.

This discovery undoubtedly belongs to the domain of the transformer, induction being the physical precedent upon which the transformer is based; indeed, a transformer is in principle an induction apparatus.

This apparatus of Faraday's showed itself to be an especially effective combination for the production of these induction phenomena. There were wound around an iron ring two separate wires of about the same length. The one coil was brought into connection with a battery, and to the ends of the other a pair of electrodes were attached. The current from the battery being sent through the primary coil, lines of force were produced which ran almost altogether in the iron core. As the core possessed only a very small magnetic resistance, the intensity of the magnetisation was very great and on closing the primary circuit a strong inductive effect on the secondary coil was produced. Faraday obtained with this apparatus the first sparks of induction. The apparatus is all the more interesting as, although not completely without poles, it at least forms a closed magnetic circuit. It has much likeness to the non-polar transformer of Zipernowsky, Déri, and Blathy, but it may be easily shown to be not entirely poleless. Poles mean, in electrical as well as magnetic circuits, those points between which the greatest difference of potential exists. A current without difference of potential can only flow in an

electrical or magnetic circuit when the loss of potential in each part of the length of the circuit, viz., the product of resistance and current, is equal to the gain of potential, that is the magneto- or electromotive force: therefore a current without difference of potential requires that the resistance and magneto- or electromotive force in each part of the length be the same. Now the magnetic resistance of a symmetrical iron ring is constant in all parts of the length of its magnetic circuit. In the case in question only one half of the ring was excited, therefore poles must have been formed at both ends of the exciting coil. The ratio of transformation of this apparatus of Faraday's was equal to the unity, so it had therefore no claim to the designation of "transformer".

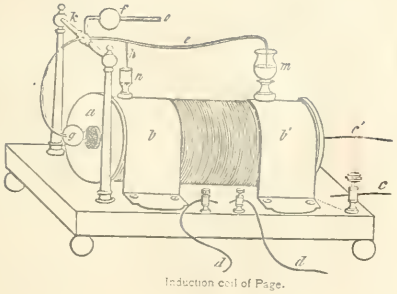
The induction apparatus of Faraday in its simplicity was in a certain measure the embryo out of which all dynamos and transformers have developed. We have seen how the first induction current was discovered by making and breaking the current from a battery in the primary coil. This method was at first adhered to, until Faraday remarked that when the secondary was quickly drawn out of or put into the primary coil, induced currents were also produced without requiring to break the circuit, the wires of the secondary coil cutting the lines of force in the magnetic field of the primary coil. He then replaced the primary coil and battery by a permanent magnet, which was likewise dipped into the induction coil.

From this and from the later development of

this invention , it follows that the question was not of a transformer in the present sense of the word, but of a secondary generator. Transformers as at present understood were first known in Europe as the Ruhmkorff's induction coil. Before we take up this invention we shall mention a much earlier and like invention, which had already been made in the United States in the year 1838. This was the induction coil of Professor Page, and was the the outcome of another invention by Professor Henry, whose apparatus was only a single induction coil. The first public notice of Professor Page's apparatus appeared in the Silliman-Journal of 12th May, 1838, under the title "Methods and trials of obtaining physiological phenomena and sparks from a heat engine by means of Professor Henry's apparatus". In May 1837, Sturgeon published, in the "Annals of electricity", in London, a description of the apparatus of Henry and Page.

Callan, an english student of physics in Minnoth, showed first, in the year 1837, that if high tension was wanted, it was necessary to employ thick wire for the primary and thin for the secondary coil. Before this time wires indeed of different lengths, but of equal cross sections, had always been employed. His apparatus was not so bad as those before known, but still stood far behind that of Professor Page.

The arrangement of Professor Page's apparatus was as follows:- Two coils of wire well insula-



Induction coil of Page.

ted from one another were wound on to a bundle of iron wires. A self-acting contact breaker was put into the primary circuit, and consisted of a double lever, having on one of its arms two parts bent downwards, so as to dip into two mercury cups.

The continuation of the lever in the other direction of the axis, which was borne by two pillars, was bent backwards, and on its end carried a cylindrical piece of iron standing before the end of the bundle of iron wires. If the primary coil were now placed in connection with a source of current, the iron core became magnetised, attracted the cylindrical piece of iron to itself, and by raising the lever the contact was broken. The iron core then lost its magnetism, released the iron armature, and the play began anew.

It will be found that this interruptor was very like that constructed many years afterwards by Léon Foucault. The effects which Page produced by means of this instrument were much more intense than those produced by Ruhmkorff with his, as Page succeeded with only a single Grove element in inducing in the secondary circuit such a high electromotive force as produced sparks 4 1/2 inches in length through a vacuum tube--a result that Ruhmkorff, although his invention created such a great and well deserved attention did not attain. In the year 1850 Page built a much larger apparatus.

In order to give some idea of the magnitude of the electro-magnetic forces which came into playhere.

suffice it to say, that the exciting coils could hold suspended in their interior an iron core weighing 520 kg. The primary or magnetising coil was of square copper wire, with a side measuring 1/4 inch, and a battery of 50 to 100 Grove elements was employed, the emersed area of the surface of the plates being 100 square inches. This apparatus gave sparks of great length. When, with maximum current strength, the primary circuit was broken, sparks of 3 inch length were received.

Ruhmkorff constructed, in the year 1848, the so-called spark-inducer named after him, the object of which was also to convert currents of low tension into those of very high tension. With this coil and like coils of larger dimensions effects were produced, but only such as were afforded by the common forms of frictional electrical machines. All things considered, it is not a little surprising that while the invention of the Ruhmkorff coil was still in its infancy, the wonderful output of Page's apparatus was still, even in the year 1851, quite unknown in Europe.

Ruhmkorff's apparatus consisted of a bobbin of good insulating material; thoroughly dried wood, or better, hard rubber. The two end pieces of the bobbin were usually made of grooved glass discs, and were bound down to the bedplate of the apparatus by two wires. Inside the coil was the already often mentioned bundle of iron wires. The primary or inducing wire was next wound upon the bobbin. As this wire had to carry currents of comparatively great strength, it consisted of only one

or afew layers of thick wire. The circuit of this coil was completed as far as two terminals on the bedplate, first passing through an interruptor like what has already been described. Over the primary coil, and after a sufficient layer of insulation had been added, the secondary wire was wound. As this wire was destined for very small currents, it was of as fine wire as it was possible to wind. In order to obtain high potential it was necessary that the secondary should possess many turns. In the earlier coils a length of between 8 and 10 kilometres was used: in the coils now made this length has been increased to between 50 and 70 kilometres. The ends of the secondary coil were connected to terminals insulated on glass pillars. It was not nearly sufficient insulation for the secondary wire to be covered with silk, but every layer was well soaked with dissolved shellac, and then well dried as it should be. A condenser, with connection with the primary coil was placed under or in the bedplate, which was usually a box. This condenser was, and is still, often made thus:--On both sides of a strip of paraffined paper, several metres long and of convenient breadth, tinfoil is stuck, at the same time leaving a sufficient margin of paper for insulation. The whole is then folded together suitably. The effect of the coil is substancially enhanced when the sheets of tinfoil are each connected to the circuit of the primary coil in such a way that the condenser is in shunt to the interruptor.

C. T. & E. B. Bright, 1855. We find a further development or modification of Page and Ruhmkorff, patented by the brothers C. T. and E. B. Bright on the 21st October, 1852, and No. 2103 in the year 1855. In the latter of these patents the inventors state what follows concerning the nature of their inventions.

Among the patents of the year 1857 there is an English one by Harrison, claiming as its object the passing of a primary current through one or more induction coils, and the connection of the secondary coils with the carbons of an arc lamp. There is nothing remarkable in the description.

The last attempt to use induction coils for industrial purposes is met with in the year 1878. In this year Jablochkoff took out a German patent, which was also carried out in practice. He required currents of very high tension to feed his kaolin lamp; at that time such currents could only be produced by induction coils.

Harrison in 1878 took out a patent having the same object as his of the year 1857. Both patents proposed the connection of induction coils in series. This is especially clearly mentioned in the latter of these, as there he says that both induction coils are put in circuit at intervals along the mainlead or primary circuit, so that one or more coils are near the places where lamps are to be fed.

We find in Meriten's English patent of the year 1878 the series connection of primary coils in the dynamo circuit also described.

Meritens intended to employ in place of the many

separately insulated circuits of the alternating dynamos of that time, only a single circuit, fed from one large or several smaller dynamos. A large number of induction coils connected in series, were to hava been distributed in the different districts of a city. Besides this, Meritens made a combenation of the secondary coils, so that heawas in a position to produce currents and potentials of various dimensions.

We now come to an inventor, who, in his time, exercised a great influence upon electric lighting by means of transformers, and whose system was in every way a great advance in those of his foregoers. Ihis man was named Bim Billings Fuller. He began to study electric lighting in his labaratory at Brooklyn in the year 1874, giving his whole energy for this object. Fuller's system of cnrrent distribution was first patented in America in the year 1878. His apparatus consisted of an induction coil on which an electric lamp was mounted, to all appearances a Jablochkoff candle. The induction coil to which we shall return later on, was built in the form of two horse shoe magnets joined together, and having consequent poles at the small coils in the middle, after the manner of the magnets of a Gramme machine. The four large coils are the primary or exciting, the four small coils on the poles of the double magnets are the secondary coils.

In the year 1880 Edward Henry Gordon took out an English patent. He had constructed an electric lamp based on the fact that when a current of sufficient electromotive force was passed over the space between two

balls of platinum or platinum iridum, the balls were rendered glowing white. These balls were suspended by thin platinum wire, or the supports were of platinum, serving also to carry the current. For the production of owerspringing sparks, it is well known that a great difference of potential is necessary, so Gordon was obliged to have recourse to induction coils, which he intended to excite by means of magneto-electric machines, or alternating current dynamos. In his patent he describes how this idea should be carried out and he actually did feed two lamps of 50 c.p., or one of 100 c.p. The apparatus is described as follows:--"The primary consists of a bundle of iron wire 1.3 inch diameter, and 18 inches long. Three layers of insulated wire 0.08 inch in diameter are wound on it. The secondary is wound on an insulating tube, and consists of about two-thirds of a mile of wire 0.0075 inch diameter, covered four times with silk. It is wound in 60 discs." "There are three binding screws, one at each end and one in the centre, so that the whole coil or either half separately, can be used for one lamp."

We do not find in Gordon's patent the slightest indication which would justify us in ascribing to him the invention of a system of distribution by transformers as known at the present day, but, on the contrary, it is clearly stown that the fundamental conditions of such a system of distribution were unknown to him, for he laid the chief weight upon connecting the induction coils in series and on the production of high electromotive force necessary for his lamp. Over and above this , he was of opinion,

as he stated prominently, that the more advantageous kiud of dynamo wai one such as that icf de Meritens, having many coils of thin wire, which were connected to separately insulated leads.

Let us look back upon the inventions which were made in the domain of electric lighting by transformers from the time of Faraday's discovery of induction up to the year 1880. There we see that three distinct characteristics were posressed by all the systems invented up to that year. These three characteristics lay in the construction, the ration of transformation, and the method of employing the transformers. Single transformers, with two or more poles were used. The ratio was either 1:1, in which case the induction coil is really not a transformer, or it was from a low to a high electromotive force; but nowhere do we find that the currents of high electromotive force were converted into those of low electromotive force. The idea in the use of transformers was that of division, not that of distribution of electric energy. The difference between division and distribution of electric energy is, in the main, as follows. By a division of electrical energy it is meant that a fixed amount of produced energy is divided into pre-determined parts of a certain number and size, while it remains indifferent, as far as the total energy is concerned, in what manner and how many icf these parts are usefully employed. By distribution of electrical energy it is meant, on the other hand, that the energy produced is variable according to the variable requirements of consumption, the maximum requirement being pre-determined from the number and size of the local

requirements, which also vary relatively to one another. Of the last of these systems there is no indication in any of the inventions of induction coils up to this date.

If we seek for the cause of these characteristics we find that the reason why transformers with two or more poles were constructed is, that the electricians of ttose days either did not know or did not understand the principles on which a proper transformer should be constructed. With them the idea of a magnetic pole acting on a wire near it was always present; while they entirely overlooked the fact that the electro-magnetic force, not the pole produced the electromotive force in the wire. On account of this they were of opinion that free poles in a transformer were not only not a drawback, but, on the other hand, a distinct advantage.

We find that Fuller especially held this view. He sought not only to have in his apparatus two simple poles, but double poles, and indeed, he patented this arrangement of his transformer.

We must bear in mind that, as far as the ratio and idea of employment of a transformer are concerned, the problem at that time was quite another to what it is now. At present the transformer serves principally to render possible the carrying of the current to a great distance economically. The electricians of those days were not so far advanced as to be able to run arc lamps independently of one another on the same circuit, and this they held quite impossible , wether the lamps

were connected in parallels or series. That apparatus was thought to be good which allowed separately insulated currents to be led from one source of current , each separate circuit going to feed a single lamp. The chief reason for this view lay in the fact that the extinguishing of all the lamps in one circuit could easily take place through the fault of one of them. At that time , when an arc lamp was cut out of circuit, it was replaced by a fixed resistance, instead of which it was thought that induction coils would have suited well. It may be casually mentioned that owing to this fact too sanguine hopes of the solution of the problem of independent working of lamps were aroused, through a want of sufficient knowledge of the laws of induction. There have also been apparatus other than induction coils used for the purpose of making the points of consumption independent of one another. We can only now recall the patent of Jablochkoff, which is based on the principle of connecting condensers into branches of a quickly alternating main current, from which arc lamps, &c. were fed.

There were no transformers in those days which in the present sense of the word "transformer", convert high electromotive force to low to suit the consumers. On the contrary the apparatus, which was then used in electric lighting plant, was such as converted low into high electromotive force, or such that the ratio was 1:1, or nearly so, according as it was determined by the connection in series of the primary coils, and the difference of potential at the consumption devices; for example, the induction coils of B. Ruhmkorff, Jablochkoff, and Gordon.

When, however, the term high electromotive force is met with in descriptions of the apparatus of that time, it must be taken to mean a great difference of potential between the terminals of the dynamo, not between the primary terminals of the transformers. Take, for instance, 100 transformers connected in series, run with a difference of potential at the dynamo of 1000 volts, although it was not known at that time how to produce so high an electromotive force, still would give across the primary terminals of each transformer the modest difference of potential of 10 volts. In this way the difference of potential at the generator was determined by the number of transformers in series. This system had plainly the great disadvantage, that no matter how tortuous a path the lead must follow, it had to pass through the primary coils of all the transformers, and the principles of a proper system of distribution were not present.

With the invention of the incandescent lamp the activity of inventors was given quite another direction. The systems of electric lighting up to this time were not sufficiently advanced to permit even of a division of the electric light, that is, the ability to feed even a small number of lamps from one generator. We shall only mention this invention so far as it helps to further the history of the transformer.

Gramme made the earliest arc lamp that could be employed alone; then followed Jablochkoff, as the first who carried out practically, and with good results, the use of arc lamps in series or in parallel arc with condensers. Siemens and Halske then replaced the Jabloch-

koff candles with their diffenential lamp, which, although not offehing an opportunity for a good division of light, was unexcelled in construction and manufacture, pointing out the way for further progress in arc lighting.

Marcel Depréz has laid down in a work of his the laws which make it possible to hold the points of consumption of electric energy independent of one another, and, excepting some inexactnesses which crept into his representation, these laws have been almost all been carried out in practice since that time.

The system of direct distribution to glow lamps had the one well known serious drawback, viz. that it only allowed of limited employment, because the cost of the leads, with equal loss of energy, increased with the square of the distance from the source of csrrent.

It was therefore obligatory, in order to carry the current economically to greater distances, to seek new means and ways, without rendering inefficient the only practical system of connecting incandescent lamps in parallel. The experience which had already been gained in the economical carrying of high tension currents with arc lamps in series, pointed out that high tension currents should be used, and that in the secondary circuits of transformers fed by such a current, consuming devices could be connected as might be desired.

Haitzema Enuma , in the year 1881, was the first one to gó in that direction, and took out a patent for the feeding of glow lamps by means of transformers.

He followed the principle of making each secondary

circuit and each point of consumption independent. The means to this purpose which he thought to employ were not practical, and did not at all differ in substance from those of his predecessors. His system is remarkable for his method of connecting the induction coils in the main lead, i.e. in series, using the secondary currents from these coils to excite other coils from which tertiary currents were received, and these again were further used to excite quaternary currents, and so in.

In May 1885 a system of current distribution by transformers was concieved by Zipernowsky, Déri and Blatky. The concieved the idea of closing the magnetic circuit of induction coils.

If indeed earlier inventors proposed for other purposes magnetically closed induction coils, the fame due to the birth of proper non-polar transformers, in which the whole of the primary and secondary turns have a like position relatively to the magnetic-field, first invented, carried out, and combined into a self-regulating system of current distribution, belongs undoubtedly to Messrs. Zipernousky, Déri, and Bláthy.

It would have been thought that after the direct distribution of current to glow lamps had taken up a determined position, it would not have been difficult to discover a self-regulating system of distribution with transformers. However, the fact shows this was not the case, for after the Edison lighting system was long known, we find such electricians as Haitzema Enuma, Gaulard and Kennedy, experimenting with the series system of connection; indeed the last of these even de-

ters his colleagues from the attempt to run transformers in parallel, because he openly held the opinion that this method of connection was impracticable.

We have here the development of current distribution by means of transformers, as it completed itself in Europe. The American electricians however, made the matter somewhat easier. They quietly waited until the invention gave useful results in Europe, and simply imported it.

But since they imported it the development of the transformer in America has been by strides and jumps, and today we have upon the market many special forms of transformers, each for their own and special class of work.

Among the first to follow closely the steps of some of the inventors in Europe already mentioned, is Mr. Stanley of the Westinghouse Company. Stanley first noticed the effects of the self induction in a circuit while measuring vacua in incandescent lamps. He began almost immediately to experiment with the transformers built after the type of Gibbs and Gaulard, which was not a very decided step from the apparatus he had been using. Although he abandoned this system under suggestion, it was not until he had found out the advantage of working the iron in the cores at nearly saturation, to provide nearer perfect regulation.

Upon the anticipation of reducing the reluctance in the magnetic circuit, and consequently the magnetizing current which had been abnormally high in European transformers, Stanley reverted to the type used

by Faraday and built a transformer which was an application of his (Faraday's) ring, very similar to the ring of Pacinotti armature of today. To further reduce the reluctance he made the ring ironclad with a core; but this was soon abandoned on account of expense. About this time the question of lamination was engaging the attention of inventors, and its application to transformers was opportune.

The type then adopted by the Westinghouse Company, and still used by them, was designed by Albert Schmidt. It represents the nearest perfection now reached in transformer work and the design for a better one is hardly necessary when we find an efficiency of 98.5 p.c. not uncommon on their largest types. The coils were lathe wound and placed side by side, being well insulated from each other and the core. The core was built up of plates, stamped from annealed sheet of the purest iron, magnetically insulated with paper.

The plates were built up by splitting one side on either side of the tongue, and folding back these sides while the tongue is thrust through the coil when they are bent back into position. By placing these cuts on alternate sides and only insulating one side of the plates the reluctance of the circuit is greatly reduced. Since the form has not changed, a sketch further along in this paper will show the form adopted better than a description. The modifications of this type in the latest practice have been principally, (first), in the determination of the relative amounts of copper and iron; (second), in the abandoning of the paper and depending

upon the oxide produced in the anealing for insulation: (third), in the butting of the joints , instead of lapping them; this course being impossible with the oxide film present; (fourth), in the dividing of the secondary coil into two parts for commercial lighting at 110 volts or 50 volts: (fifth), and in dividing the primary in two sections, in the case of very high voltages, to insure better insulation.

Other manufacturers in America and Great Britain are building transformers which adhere practically to the above points. The form of magnetic circuit is greatly a question of argument, and various forms have their respective excellencies and defects, which each manufacturer necessarily thinks his own transformer possesses to the best advantage. Mr. Stillwell sums up the conditions in a very pertinent manner when he says: "The designer of a transformer has presented to him alternate paths. He may easily design with reference to a very small loss of energy and relative high efficiency at light loads, if he is willing to sacrifice regulation. He may design a transformer of little weight and large output, if he is content to work at a very high temperature and endanger the lasting qualities of his insulation."

"Extraordinary excellence in one respect is only obtained at the price of sacrificing excellence with respect to other properties equally important."

Transformers are now built to almost any size the mechanical diffeculties being the limiting factors.

Cooling devices are used in the larger units and oil insulation. Although this insulation has objections the indestructibility of the dielectric favors its adoption. 20,000 volts is already a reality and 60,000 volts a grave possibility, the line insulation and not the transformer being the determining element.

THE FUNDAMENTAL PRINCIPLES.

The fundamental principles.

The alternating current transformer is the simplest of alternating current apparatus. The primary circuit is excited by an impressed E.M.F., while in the secondary circuit an E.M.F. is induced. Thus, in the primary circuit power is consumed, and in the secondary circuit a corresponding amount of power is produced.

If the magnetic induction through a circuit changes, due to any cause whatever, an E.M.F. is developed in circuit proportional to the rate of change of the magnetic induction, or, we may write: $e = -\frac{dn}{dt}$ using the negative sign to indicate that a positive change will give a negative E.M.F., n being the maximum flux through the core. Or we may say that the E.M.F. is proportional to the rate of cutting in the C. G. S. system. To reduce this to the practical system the value must be divided by 10^8. The practical unit being the volt, we may write $e = \frac{-dn}{dt} \times 10^{-8}$

This is the value of the E.M.F. per turn and if there are (S) turns the equation becomes $e = -S \frac{dn}{dt} 10^{-8}$.

In consequence of the flow of E.M.F. in the primary we have a flow of current which will change as the E.M.F. changes. This change of current will produce in the primary an E.M.F. which will depend upon the rate of change of the current in the circuit, or $e = -L \frac{di}{dt}$.

When the coefficient L is a constant of the circuit, termed the coefficient of self-induction, which depends upon the form of the circuit, the practical unit being the (henry) which is equal to the ratio of the induced electromotive force to the time rate of change of the current producing it. The current being in amperes and the E.M.F. in volts.

This E.M.F. always opposes any change in the value of the current. In the transformer the induction is low, and the permeability is considered constant without appreciable error and we may equate them to equations because of the law of conservation of energy. The action and reaction are equal. $L \dot{I} = S N$

$$L = \frac{S N}{I}$$

Or we may state that the coefficient of self-induction is the ratio of the number of flux-turns to the current producing them.

In the same way we may find the induction of both coils (primary & secondary) considered. Where M is the coefficient of mutual induction as before we may write:

$$e_2 = -M \frac{d \dot{I}_1}{d t}$$

and $$e_2 = S I \frac{d N}{d t}$$

where N is the flux through the secondary winding

and is proportional to the primary current

$$\text{or} \quad M i_1 = S_2 N$$

$$M = \frac{S_2 N}{I_1}$$

The coefficient of mutual induction being the ratio of the number of lines in one circuit to the current in the other circuit which produces them.

From the above it is evident that the induction of the primary must thread the secondary circuit to produce a current in it. The relation between the two circuits being strictly mutual.

E.M.F. produced in the secondary.

With a sine E.M.F. applied at the primary, the resulting current will be of the sine form. With the secondary open we have a simple series circuit containing resistance and self-induction.

The primary current is:

$$i_1 = E_1 \sin\left(\omega t - \tan^{-1} \frac{L_1 \omega}{R_1}\right)$$

$$\sqrt{[R_1^2 + (L_1 \omega)^2]}$$

$$i = I_1 \sin \omega t - \tan^{-1} L_1 \omega / R_1$$

The instantaneous value of the magnetic flux will be

$$\Phi_1 = 4 \pi S_1 A \mu I_1 \sin(\omega t - \tan^{-1} L_1 \omega / R_1)$$

The maxvalue is:

$$N = 4\pi S_1 A\mu I_1/l$$

Now the number of lines of force which will cut the secondary in one complete cycle is $4 S_2 N$ and assuming one cycle per second, we have for the average E.M.F. induced in the secondary $E2 = 4 S_2 N \times 10^{-8}$ volts and if the frequency is (f) cycles per sec. average

$$E2 = 4 S_2 N f \times 10^{-8}$$

but we have for a sine wave

$$\frac{\text{Average } E}{\text{Maximum } E} = 2/\pi: \quad \text{Max. } E_2 = \frac{2\pi S_2 N f}{10^{-8}}$$

We also have

$$\frac{\text{Virtual } E}{} = \sqrt{2}\pi S_2 N f \times 10^{-8}$$

The primary E.M.F.

The changing magnetic flux which induces an E.M.F. in the secondary coil will also induce a counter E.M.F. in the primary which will be similar to the equation for that induced in the secondary. So substituting S_1 for S_2 we get

$$\text{Max } E_1 = 2 S_1 N f/10^8 = L\omega I_1/10^8$$

From the above equation we can get the relation

$$E_1/E_2 = S_1/S_2$$

which is in the assumption that there are no losses

and that the secondary carries no load.

In the same manner and under the same assumptions we will find that the currents are in the inverse proportion to the number of turns

$$\frac{I_1}{I_2} = \frac{S_2}{S_1}$$

and neglecting all these losses we can assume that the power input is equal to power output or

$$E_1 I_1 = E_2 I_2$$

INTRODUCTION.

Introduction.

Electrical energy after generation must be delivered economically and in a suitable form to the consumer. The delivery is commonly divided into two parts, namely, transmission and distribution. The former being in the most economical to the company, and the latter not only in the most economical manner, but in the form desirable to the consumer, namely to suit the existing apparatus.

The choice between two-phase and three-phase is not dependent so much upon their abstract and theoretical characteristics as it is upon the actual differences in the characteristics of two-phase and three-phase apparatus, which may exist in the generators, the transformers, the motors and in other apparatus. For example, with certain types of generators there may not be the same reason for choosing the number of phases that there may be with another type. On the other hand, as current may be used in one way in one place and in another way in another place, it may be best to select two-phase generators in one case, and three-phase generators in the other case, although the two generators may otherwise have substantially the same characteristics. The problem, then, is to determine what differences there are in apparatus, and in its operation under different conditions, between the two-phase system and the three-phase system, and to determine which, on the whole, is preferable under given conditions.

Polyphase load--as distinguished from single-phase load--is quite indifferent as to wether the cur-

rent be two-phase or three-phase. That is to say alternating-current motors, wether induction or synchronous, and rotary converters may be constructed for two-phase or for three-phase without any appreciable difference in either the cost or the performance of the machines. Likewise, alternators which supply current to motors and rotary converters, in which case each phase is equally and similarly loaded, may be wound for either two-phase or three-phase without any appreciable difference either in cost or in performance. It follows, therefore, that when polyphase alternators supply current to polyphase apparatus, any choice that there may be between two phases and three phases must be based upon features that lie outside of the machinery.

The transmission circuit is the important additional element. It is well known that with a given maximum electromotive force between wires a given power can be transmitted over three wires by three phase current with the same loss that occurs with four wires when two-phase current is employed. The three-phase current, therefore effects a saving of one wire or 25 per cent over two phase. The relative importance of this saving depends upon circumstances: if the distance be long, it is considerable: if the distance be short, it may be a matter of relative insignificance.

The transformers that may be required between apparatus and transmission circuit in certain ways favor two phases and in other ways three phases. The two transformers for a two phase circuit are obviously of less cost per kilowatt and of higher efficiency and

closer regulation than the three transformers of lesser size which would usually be used for the same aggregate output on a three phase circuit. It is true that two transformers on two phases of a three phase circuit may be used, but, besides the objection to an unsymmetrical or an unbalanced arrangement, there is less effective operation of the transformers.

For supplying current to a three phase motor or rotary converter by two transformers connected on two of the phases, it is necessary that the normal output of the transformers should be increased by approximately 17 per cent above what would otherwise be required, due to the fact that the two transformers do not operate efficiently for delivering current to the third phase.

Switches and switchboard instruments differ slightly for two-phase and for three-phase circuits. In one case switches for four wires are required and in the other case switches for three wires are usually sufficient: although when the three transformers on a three-phase circuit are to be cut out individually, each transformer requires a double-pole switch, so that six instead of three wires require switches.

Measuring instruments are usually simpler and more straightforward in their indications on a two-phase circuit than on a three-phase circuit. The readings of current and power on a two-phase circuit consisting of two parts which are fairly independent of one another, are much to be preferred, particularly for those ~~who~~ which are not skilled in the theory of alter-

nating-current measurements.

In conclusion, therefore, when polyphase load--such as motors or rotary converters--is to be served, the most important item in making a choice between the two systems lies in the transmission circuit: and the saving of conductors by the use of the three-phase system renders its selection advisable in most cases.

THE SCOTT.

The Scott.

In the previous discussion it was brought out that the three phase system is widely used, it being very efficient in many respects: but on the other hand, the consumers apparatus and motors are not always usable on the three phase system, hence the interventeon of the transformer, which at the same time is stepping down from the high line voltage, will change the phase relation from three phase to two phase.

To accomplish this end C. F. Scott in 1894 Chief Electrician of the Westinghouse Company proposed a solution of the problem requiring the use of two transformers.

To get a clear understanding of the Scott transformer it is well to consider it from the following point of view: Let us represent the three phase E.M.F. by its vectors a, b, c, in the following figure. These E.M.F.s a, b, and c, are 120° apart. Now consider any point such as (O) without an equal-lateral triangle. A.B.C., the sides of which represent the E.M.F. a, b, c, between coils of the transformer. Let the coils be represented by the lines x, y, z, which are connected in star to the three corners of the equallateral triangle. If these three coils are arranged upon two cores as in the third figure, with a definite relation between the number of turns on each, then the mains will give the symmetrical E.M.F.'s a, b, and c.

Fig 1.

Fig 2.

Fig 3.

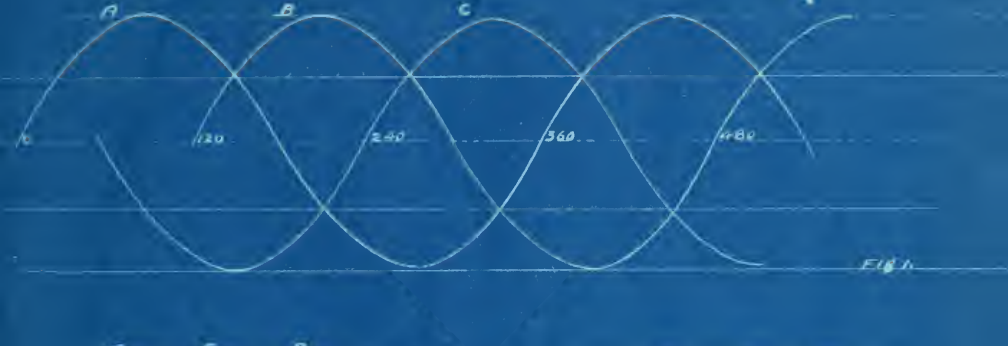


Fig 1.

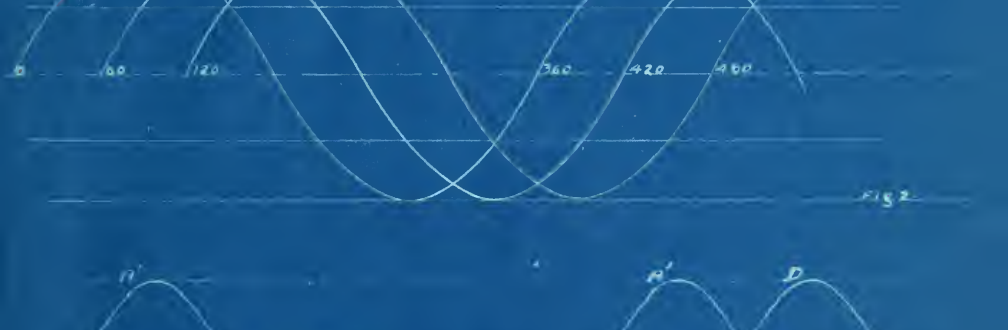


Fig 2.

Fig 3.

Fig 4.

The above is explained more clearly by the following: Starting with the assumption that we are to transform from a three phase system to a two phase system. Fig. 1 Represent the E.M.F. of the three phase system by the curves a, b, c, which are 120° apart in phase. Then the problem remains to combine the three phase E.M.F. a, b, and c in such a manner as to obtain two E.M.F. 90° apart in phase, which is the two phase relation and is represented by the curves A', D', fig. 4.

Now if we reverse one of the coils the E. M. F. waves may be represented by fig. 2, in which the E.M.F.s are 60° apart relative to each other. Now if we plot curves B and C, each having an ordinate value equal to 100 and increase the curve A to 1.73 times this value, or having an ordinate equal to 173, we may plot the curve shown in fig. 3. Now if the coils having the E.M.F.s represented by curves B and C be placed on the same core their resultant E.M.F. may be represented by the curve D in the fig. 4. Now since the portion of the curve above the axis and the portion below are similar, the point at which the resultant curve will cross the x axis will be half way between B and C. Therefore the distance from the point where the E.M.F. wave A crosses the x axis to where the curve D crosses the x axis is 60°+30° or 90° which shows that curves A and D are at quarter phase.

We may consider the curve A in figure (4) as representing the value of the magnetic flux pro-

duced in one transformer and that B and C represent the magnetic flux produced in another transformer, or the curve D representing the resultant flux of B and C of the second transformer. The fluxes A and D being of equal value and 90° apart, it is obvious that the E.M.F.s gererated by them in the secondary coils will bear the same relation to each other, hence will produce two phase currents.

In order to arrive at the above result in practical operation, two transformers having the coils as shown in fig. (5) should be connected up as shown. Transformer number (1) should have 1.73 times as many turns as 1/2 the number of turns on transformer number (2), and one side of the transformer # should be connected to the middle point of transformer number (2). It is evident that the current in the coil of transformer number one is represented by the curve A and the currents in the two coils of transformer number 2 by the curves B and C with the coil represented by curve B reversed.

A very concise way to represent the results that we have just arrived at is by use of the clock diagram, as shown in fig. 8. Let the three phase current be represented by the vectors A, B, C, which are 120° apart. Now if we reverse one coil, say C, we may represent it by the rector diagram fig. 6. As before, if we increase the number of turns on coil, we increase the E.M.F. proportionally: or we

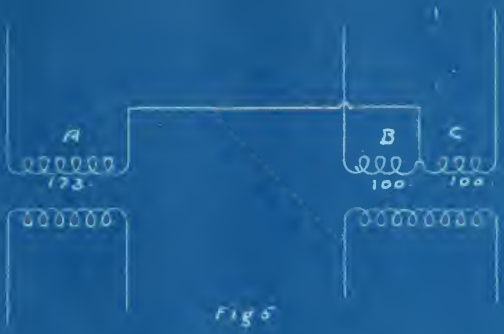
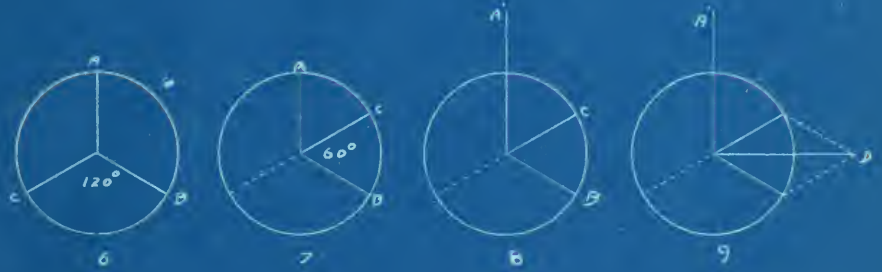

A
B
C
173.
100.
100.

Fig 5


A
B
C
120°
6
A
B
C
60°
7
A'
B
C
8
A'
D
9

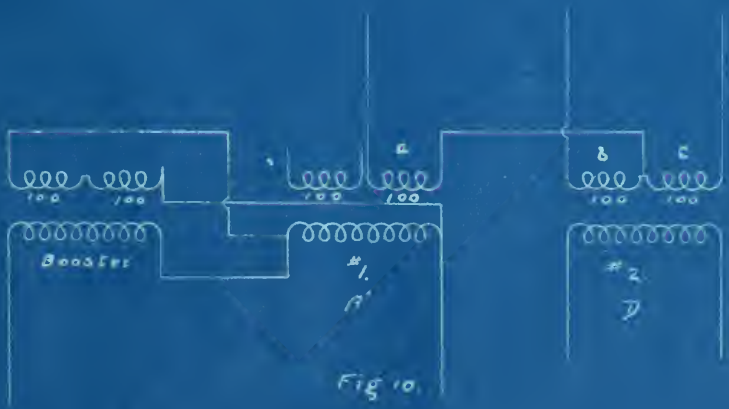

100
100
100
100
100
100
Booster
#1.
A'
#2.
D

Fig 10.

may increase the vector A to 1.73 times the value of B and C, as shown in fig. 7. Now if we combine the vectors B and C we get the resultant D fig. 8, which gives us two equal rectors at 90° apart . Fig. 9.

In practice it is not always possible to have transformers at hand whose coils have the ratio of 100 to 173 and the same results may be accomplished in the following manner. Having three transformers whose primaries can be divided and are of equal number of turns, connected up as shown in fig. 10.

As before, one side of one of the coils of transformer number 1 is connected to the middle point of transformer number 2. Now the third transformer has its primary coil connected in series with the secondary of transformer number one. By this connection it is possible to obtain a boosting effect on transformer number one, which will give very close to the proper value, giving a two phase current at the secondary terminals.

STINEMETZ'S PHASE TRANSFORMER.

Stinemetz's Phase Transformer.

A method for transforming an alternating current system comprising poly-phase electromotive forces of any given number of phase relations into a different system where the phase relation of the electromotive force corresponds to that desired, is obtainable from that given by Stinemetz. By his method almost an endless variety of phase transformations are rendered practical; but two to three and three to two phase translating devices are the ones most commonly employed.

Diagrams 1 and 2 illustrate the conversion of the three magnetomotive forces. 120 deg. apart into two forces 90 deg. apart, or vice versa.

Let a, b, c, represent the magnetomotive forces or electromotive forces of a three phase system displaced by 120 deg. in phase and of equal magnitude, and further assume that it is desired to transform these electromotive forces corresponding in regular relation to the vertical and horizontal axis.

On the diagram the vertical and horizontal rectors a^1, a^2, b^1, b^2, are drawn. Into which the forces a & b respectively may be resolved, while many in like manner may be regarded as the resultant or equivalent of a vertical rector equal in length to the line C and a zero horizontal. Now combine the force a, b and c values and directions corresponding to the virticle vectors and the re-

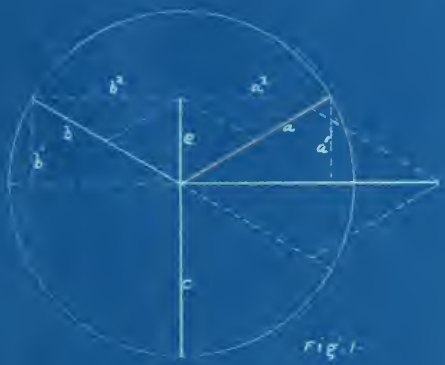


Fig. 1.

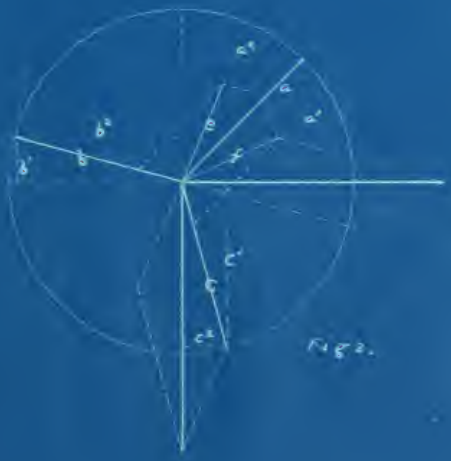


Fig. 2.

sultant will be found to be an electromotive force in the direction of the virticle axis. To show this, lay off on a & b lengths equal to a^1 and b^1 respectively and completing the parallelogram the resultant c is obtained in the virticle direction equal to the sum of c and e in value. This is one of the electromotive forces of the required quarter phase system and, as pointed out, has been secured by combining the forces in values and direction Proportional to the virticle Vectors. To secure the second electromotive force of the desired quarter phase system, lay off on line (a) length equal in value to the horizontal component (a^2) and lay off on (b) when reversed (since it will be observed that a^2, b^2, are in the opposite direction) (a) length equal to (b^2). By completing the parallelogram a second resultant is secured, which is in the horizontal direction, which is equal in value to the first resultant. From this it will be clear that the initial forces have been combined in a manner corresponding respectively to the virticle and horizontal rectors given by the parallelogram of forces drawn to represent the transformation desired, the result being two E.M.F. having the required phase difference.

This may be also accomplished by revolving the rectors into components as shown in figure 2., and neither of the original phases are assumed to correspond in direction with either of

.he required new phases.

Lay off on b an amount equal to (b^1) and on a an amount equal to a^1 as before. Complete the parallelogram reversing it and combining it with c, we have one rector of the two phase diagram. By taking a rector on (c) equal to c^2, and again on a equal to a^1, we get the resultant f. Combining this with (b) (reverved) we get the remaining resultant vector of the two phase diagram.

SINGLE PHASE TO THREE PHASE.

Single phase to three phase.

In the previous discussion I have taken up the subject of transforming from two to three phase and three to two phase because that seems to be the most common practice.

It sometimes happens that lighting plants are designed with no thought of ever having a motor load, and it has seemed necessary to produce a single phase motor, which has not always given satisfaction. To get around the necessity of using a single phase motor a transformer has been devised by which a single phase current may be transformed into a three phase current.

By referring to fig. 1, the following will give a conception of how a three phase current may be obtained from a single phase current. Fig. 1 is a diagram of the phasing transformer with connections to the three phase motor. A being the generator, B the simple section of the transformer, D the condenser, and M the motor: R, primary of the simple section of the transformer, N and L, primary of the compound section: G, H, and I, secondaries of the simple section of the transformer, and J and K secondaries of the compound section. The primary of the simple section of the transformer is in series with the compound section, and condenser. By the proper adjustment of capacity and inductance, the magnetic flux in the core of the compound section is approximately 90 degrees in phase behind the simple section, then, in order to get three phases from the two, We resort to resultants in the secondaries: G and K constitute one phase, H and J a second, and I the third.

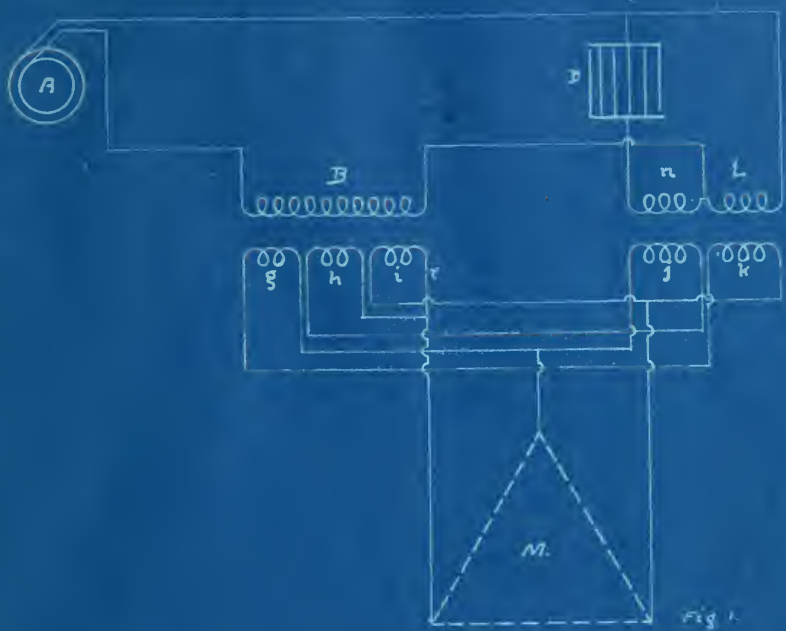


Fig 1.

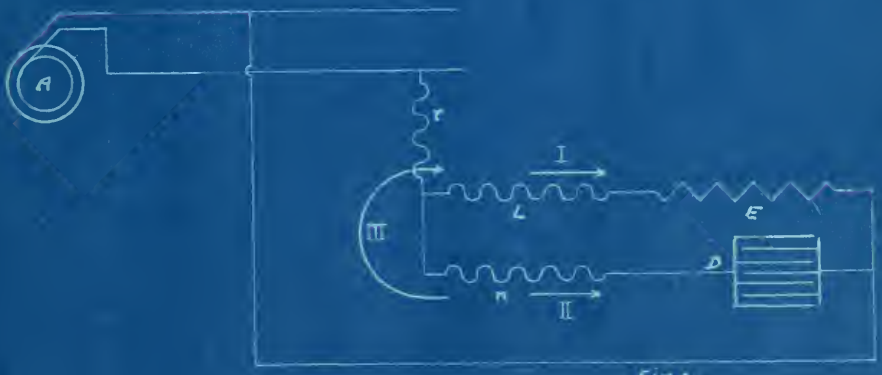


Fig 2.

The essence of this invention rests in the arrangement of the compound section of the transformer and condenser. In order to explain the theory involved in this, refer to fig. 2, in which A is the generator, E, the inductance, D, a condenser or capacity, L and N represent the leads to the inductance E, and to the capacity D. If the generator is generating an electromotive force in the direction of the arrow, fig. 2, a current will flow through the lead L and the inductance E, as represented by the arrow prime, and through N into D, in the direction of the arrow second, as indicated by the curves in fig. 3: that is, during the rise of the electromotive force through the machine from the point, O, to the top of the wave at P, the current will flow in parallel into or through the inductance E, and the capacity D, fig. 2. As soon as the wave of the electromotive force commences to decline from the point P, the condenser will begin to discharge and the current flowing from it, will be in the direction of the arrow third, fig. 2. Also, at the same time, the inductance will discharge its energy by a current in the direction of arrow third, so that the current represented by arrow third will cross the zero line at point T, fig. 3, or is delayed by a time equal to 90 degrees. Thus, we see that the current represented by arrow third will be lagging in its time period considerably behind that in the lead R, represented by O-P. Now, if we wind the lead L and the lead N , upon an iron core as shown in fig. 4, in opposite directions and of the same number of turns, and have the inductance

E bear a proper relation to the capacity D, so that the currents represented by arrow prime and arrow second shall be equal, no magnetic flux will be produced in the core during the rise of the potential of the machine from O to P on the curve, but during the fall of the electromotive force of the machine, and during the discharge of the inductance and condenser which is represented by arrow third, fig. 2, the currents flowing through N and L will be in series and flowing in the same direction: consequently, the magnetic flux will be approximately 90 degrees later than it would be if charged directly from the machine. We have represented in fig. 2, a section of lead by R, and it will now be clearly seen that the current in the lead R, will have a phase difference from the combined or resultant phases in the leads L and N. Furthermore, a current in the lead R will be in the lead of the electromotive force of the machine, because the inductance and the condenser, previously described, cut off the flow of the current before the machine has reached the zero point, and when the lead R is placed upon an iron core as shown in fig. 4, it has a tendency to lag, which counterbalances the lead and leaves the main line current somewhere near in phase with the E. M. F. of the generator.

Refer now to fig. 4, where the leads L and N are wound in opposite directions, and completely interlaced upon the iron core L, the generator, inductance and capacity being indicated by the same symbols as in the previous figures. The lead R is here wound upon the

Fig 3.

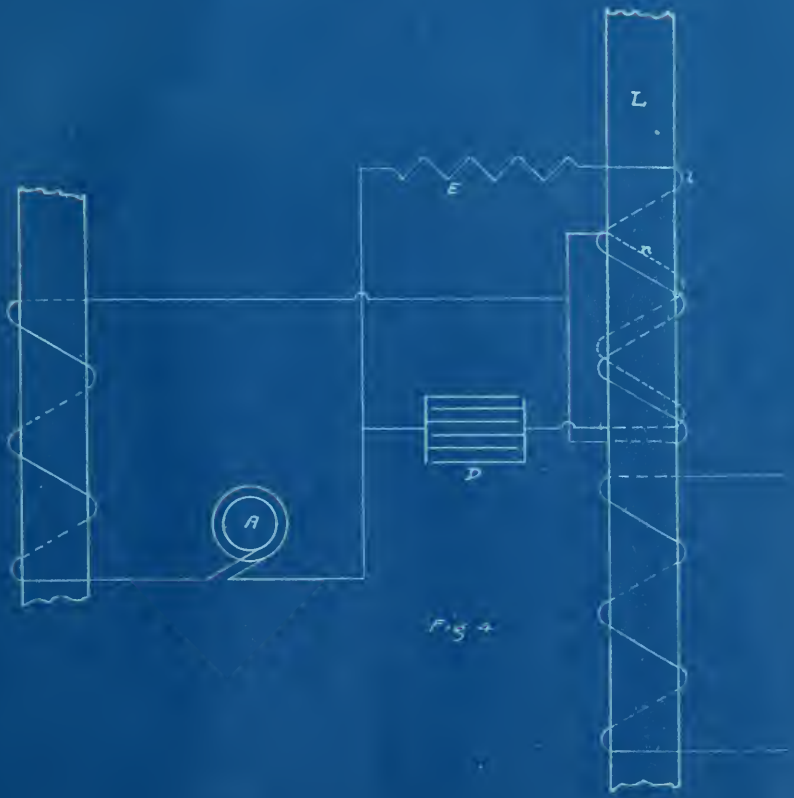


Fig 4

second iron core, which constitutes the primary of the simple section of the transformer as shown at B, fig. 1. In reducing to practice and applying the transformer to an induction motor, we find that the inductance E, can be dispensed with, as the apparent inductance produced by the motor furnishes all the lag necessary and, it will be noted, that in fig. 1, the extra inductance is left out of the combination. The lead from the simple section of the transformer, it will be noted, goes to the center of the compound section, for the winding N and L are together, or, as before mentioned, interlaced upon the core. The magnetic flux in the two sections of the transformerare approximately 90 degrees apart. The secondaries are therefore wound each partially upon the two cores, so that the three resultant phases may be produced from two.

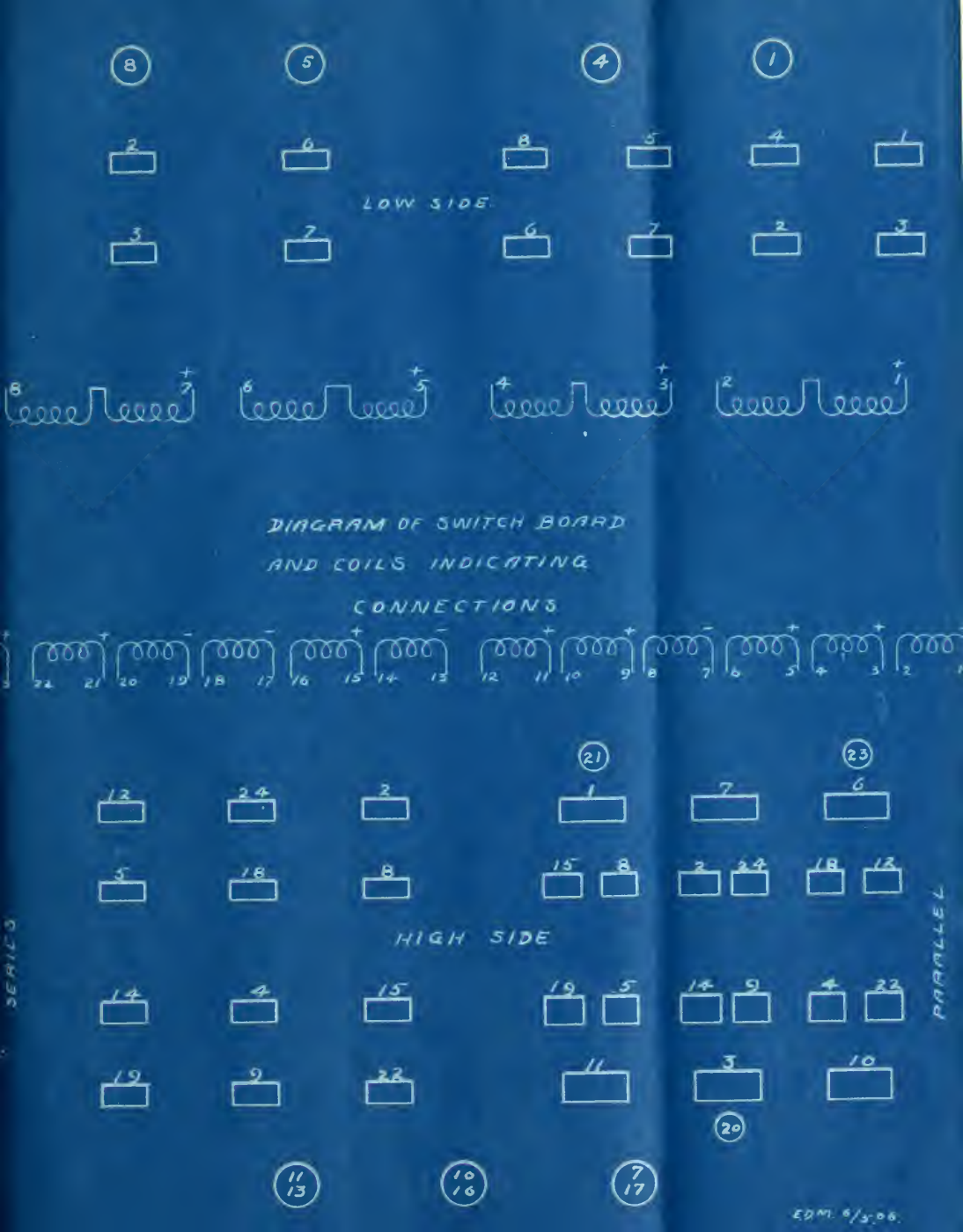
DISCUSSION.

Discussion.

It is my regret that I can not give a report at length on the transformer under consideration. I have drawn up diagrams of the coils as they exist, also Vector diagrams of the relative relation of the various fluxes or E.M.F.s in the coils, later, I have given Vector diagrams showing what I think should be the Vector relations in the transformer to properly phase from two to three, or three to two.

On the following page is a diagram of the switchboard terminals and switch contacts together with a diagram of the coils on the two cores. Each terminal and switch contact was numbered, also the terminals of the coils were numbered with little brass tags indicating the direction in which the coil is wound upon the core. That is, if the positive terminal of a source of E.M.F. is connected to the terminals marked postive, the fluxes in these coils will be in the same direction.

Fig 1. Commencing with the terminals at the top of the page, which are the terminals for the two phase side of the transformer, terminals 1 to 4 constitute one phase and 5 to 8 constitute the other phase. Now, considering this side of the transformer, which is the low side, if the switch be thrown to the right the low coils are connected in parallel, that is, terminal 1 & 3 are connected together and to the same binding post,


8
5
4
1
2
6
8
5
4
1
LOW SIDE
3
7
6
7
2
3
8
7
6
5
4
3
2
1
DIAGRAM OF SWITCH BOARD
AND COILS INDICATING
CONNECTIONS
24 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2
21
23
12
24
2
1
7
6
5
18
8
15
8
2
24
18
12
HIGH SIDE
14
4
15
19
5
14
9
4
22
19
9
22
11
3
10
20
11
13
10
16
7
17
SERIES
PARALLEL
EDM. 6/3-06.

while 2 & 4, 5 & 7, 8 & 6, are done in the same way. With the switch thrown to the left the coils are connected in series.

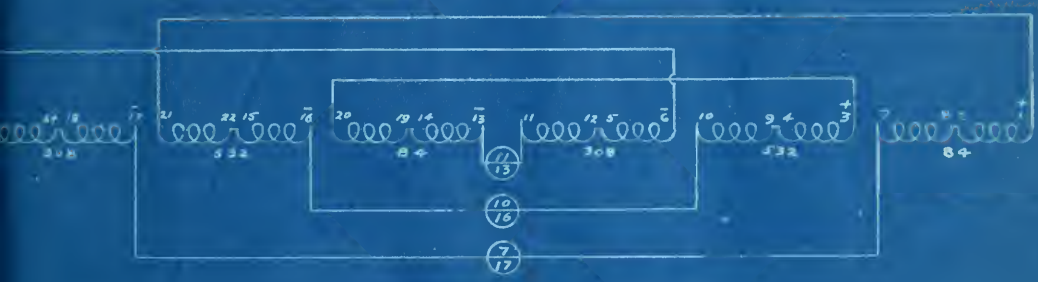
The high side is connected delta. It is a delta winding distributed on two cores. The coils from 1 to 12 indicating those of one core, and from 13 to 24 those on the other.

The inter. connections between the two sides is indicated; terminals 21 and 1 being permanently connected together, also 7 and 17, 23 and 6, 11 and 13, 3 and 20, 10 and 16, making points 7, 10 and 11 as corners of the delta. Now if the double pole switch be thrown to the right, all the coils on each core will be thrown in parallel with the coils on that core which are of the same number of turns. If the switch be thrown to the left these same coils will be thrown in series, that is, those with equal number of turns.

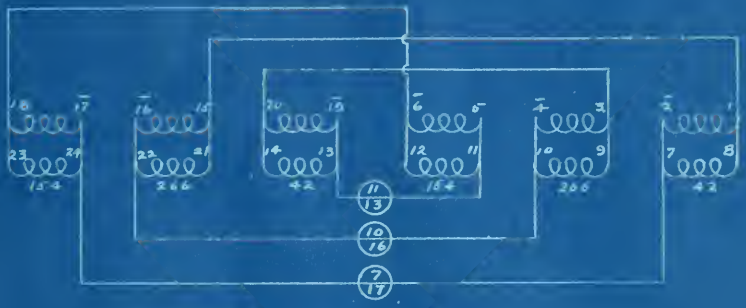
The above relations are shown very clearly by the following wiring diagrams and the rector diagram is shown immediately below. Considering the diagrams from the viewpoint of fluxes and the diagram in the counter clock wise direction also that from the center out will represent a postive direction of flux when a postive terminal of a source of E.M.F. is connected to the postive terminal of the coil. (This above being purely arbitrary assumption.)

Consider the first coil to the right of the center the E.M.F. or flux due to that coil can be represented by the rector (o a) either series or

SERIES CONNECTION



PARALLEL CONNECTION.



parallel. The E.M.F. of the next coil to the right may be represented by the rector (o b) (dotted) and the last coil to the right on that one core by the rector (o c) (dotted). The above holds good either for series or parallel. Now consider the coils on the left of the center of the diagram or the coils on the remaining core. In series with the first coil considered is a coil on the other core of equal number of turns and its direction is represented by the rector (o a') (dashes). The coil on the left in series with the second coil on the right is represented by (o b') (dashes) and the last coil by (o c') (dashes).

It will be noticed that the directions of the E.M.F.s of a three phase current applied at the terminals and represented by the above rectors are 120° apart for the left side, and on the right 60° apart, being that (o a) being reversed. Now to combine these rectors so that the resultant magnetomotive forces, due to the E.M.F.s in the several coils, will be 90° apart. Reverse the coil represented by (o c) on the right (1 to 7) and the coil represented by (o c') on the left (16 to 21). This will give the rectors (o A), (A B), and (B C) whose resultant is the rector (o C), which is the resultant magnetomotive force for the right side and (o C') for the left side.

The number of turns representing the coils of several rectors is marked on the rector.

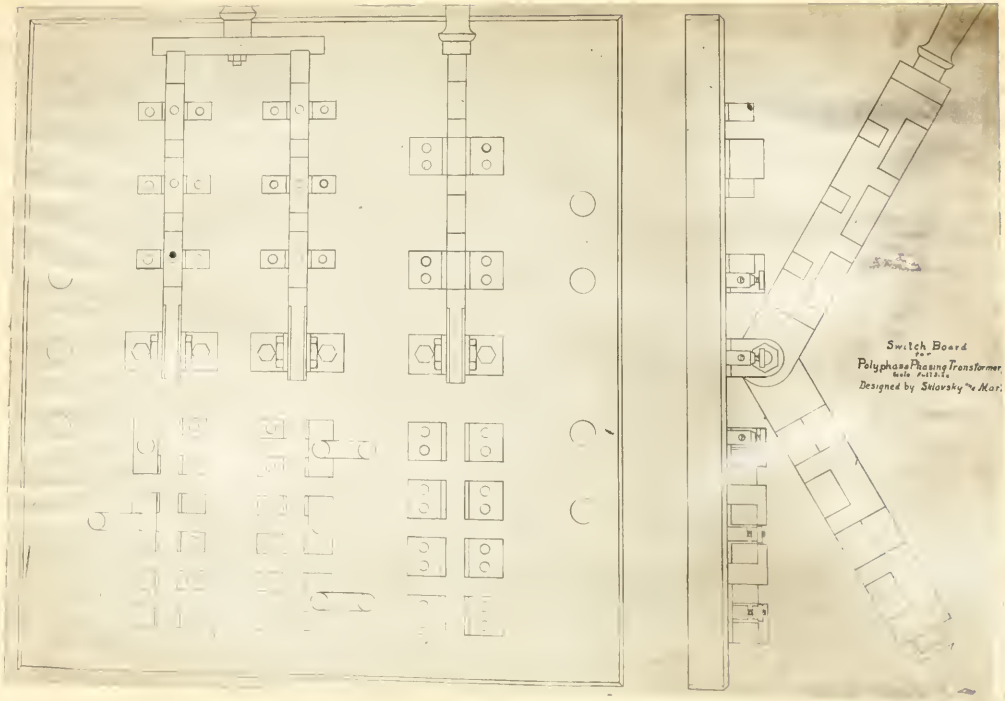
The aboye scheme for transforming from three phase to two phase is all right: but it is not reversable.

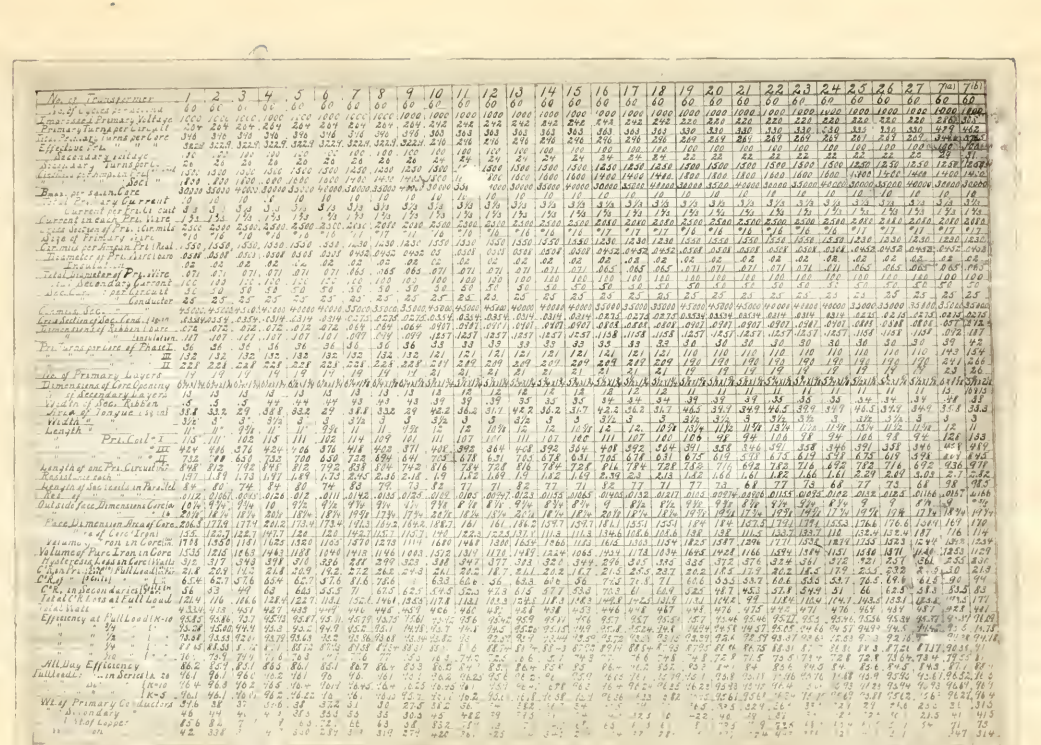
It is impossible to transform with the above from two to three phase with the given number of turns. To make it possible and to have a diagram which is perfectly balanced I would suggest that the number of turns be changed slightly to meet the requirements in the following diagram .(Fig.2).

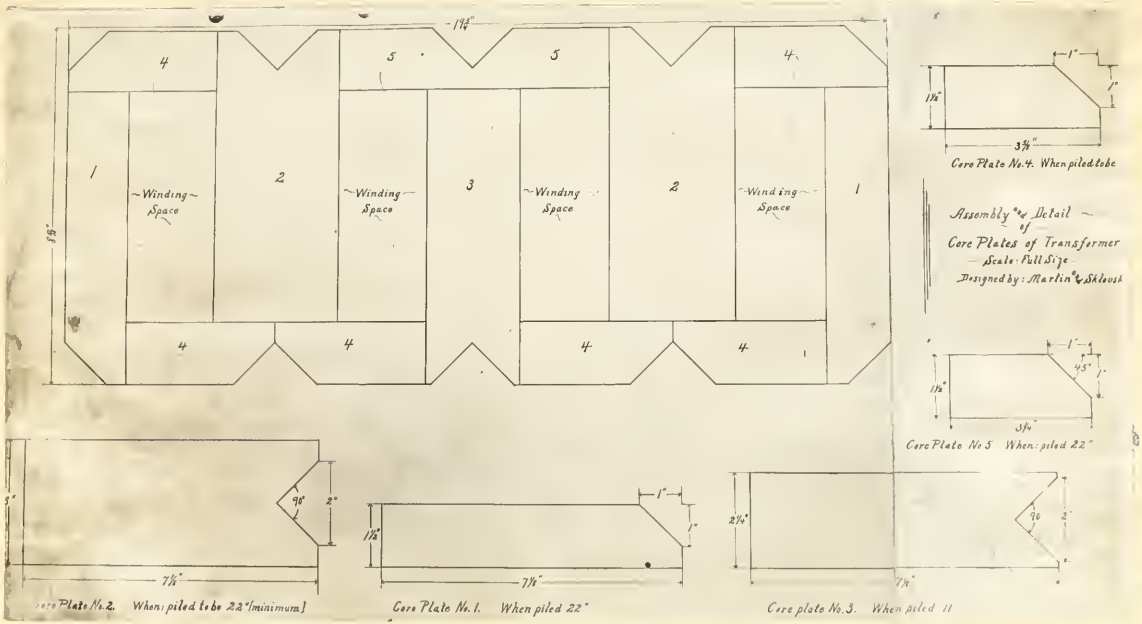
That is that the coils of 154 turns be made equal to (a cos 45°) the coils of 42 turns be made equal to (b) sin 15°) and the coils of 266 turns be made equal to (c) cos 15°) where ,a ,b ,c) are equal to each other and to some constant.

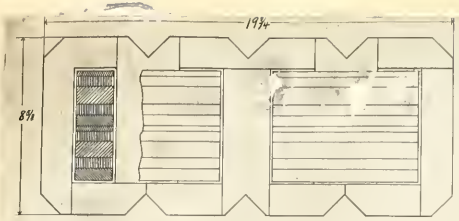
If the number of turns per circuit and core be kept constant the change mechanically will be made possible.

I wish to heartily thank Professor C. E. Freeman, Professor E. Snow and Professor E. H. Freeman for their many valuable suggestions and interest which they took in the work.

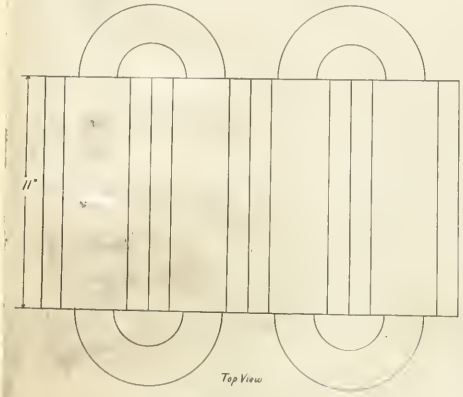

Switch Board
for
Polyphase Phasing Transformer
Scale F.S.D.C.
Designed by Selovsky & Kar.




19¾"
4
5
5
4
1
Winding Space
2
Winding Space
3
Winding Space
2
Winding Space
1
4
4
4
4
15"
1"
1"
1½"
3¾"
Core Plate No. 4. When piled to be
Assembly & Detail of Core Plates of Transformer
Scale: Full Size
Designed by: Martin & Skloosh
1"
45°
1"
1½"
3¼"
Core Plate No 5 When piled 22"
90°
2"
7⅛"
Core Plate No. 2. When piled to be 22" (minimum)
1"
1"
1⅞"
7⅛"
Core Plate No. 1. When piled 22"
2¼"
90
2"
7⅛"
Core plate No. 3. When piled 11

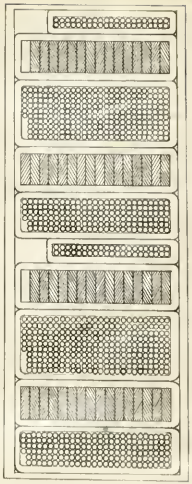


Front & Sectional View



Top View

Polyphase Phasing Transformer
10 KW. 3-2, 2-3rd 3-1 Phase Scale 1 S.



Assembled Cross Sections of Conductor and Insulation
Scale. 2 Size